Research Models of Helix Waveguides

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A satisfactory technique of constructing research models of helix waveguides has been evolved. A helix of insulated copper wire is wound on a mandrel and surrounded by a sheath of lossy material which, in turn, is covered by an outer plastic jacket reinforced with fiberglass. Units with 2-inch inside diameters have been made in lengths of 18 and 112 inches with observed circular-electric-wave losses 90 per cent above theory for an ideal copper tube at 55,000 mc.

In short lengths, the helix waveguide provides a useful component known as a mode filter which may be inserted at intervals in a solid-wall waveguide transmission line. The long lengths are of interest in producing an all-helix waveguide, which is expected to have superior transmission properties.

I. INTRODUCTION

A cylindrical metallic waveguide provides a unique transmission line for a circular electric wave having a wavelength less than one third the inside diameter of the waveguide. Under such conditions the lowest circular electric wave, TE_{01}, has less loss than any other mode. Furthermore, for perfectly round straight pipe, the losses for this mode decrease indefinitely as the frequency increases. Unlike all other modes, the circular electric modes induce no longitudinal wall currents. The currents which do flow are in the circumferential direction and result from the action of the pipe in restricting and directing the propagating energy.

Rigorous theory and experimental data substantiating the validity of the above statements have been presented elsewhere. (Refs. 1 through 6). The usefulness of these properties has provided the stimulus for a comprehensive study by Bell Telephone Laboratories at Holmdel, N. J. For this purpose, a round waveguide having a 2-inch inside diameter has been selected, and it is anticipated that its transmission will be useful over the band from 35,000 to 75,000 megacycles. Aside from economic considerations, the penalty for using a larger diameter is that the number of parasitic modes which may propagate is greatly increased and the physical tolerances become more critical.

There are numerous ways by which parasitic modes may be generated. Some of the most troublesome causes are axial discontinuities such as sharp bends, steps at junctions and ovality inside the pipe. Even though such mechanical irregularities are reduced to a practical minimum, it has been shown that the residue still produces electrical effects which are more than can be tolerated, (Ref. 5, pp. 1227–1229). One method of reducing effects of unwanted modes is to add mode filters at intervals along the line. An early version of such a device (Ref. 6, p. 1127), shown in Fig. 1, consisted of a succession of transverse copper rings separated from each other by spacer rings of lossy dielectric. This provides poor longitudinal conductivity but good circumferential conductivity, so that the losses for the circular electric wave group remain low while those for other modes become substantial. Since the unwanted energy is dissipated in the lossy medium, there is no possibility of reconversion to the circular electric mode. In the absence of such mode filters, the intermode effects cause serious distortion of the signal wave, because of a difference between the phase constants of the interfering mode and the signal mode, (Ref. 5, pp. 1230–1239).

A structure analogous to the one briefly described above but easier to construct has been developed and is illustrated in the cutaway view of Fig. 2. The completed structure is best described as a sheathed helix waveguide. The inner waveguide surface is a closely wound helix of insulated copper wire which is substituted for the spaced rings of its predecessor. The helix is surrounded by a lossy sheath and this, in turn,

Fig. 1 — Spaced-disk mode filters.

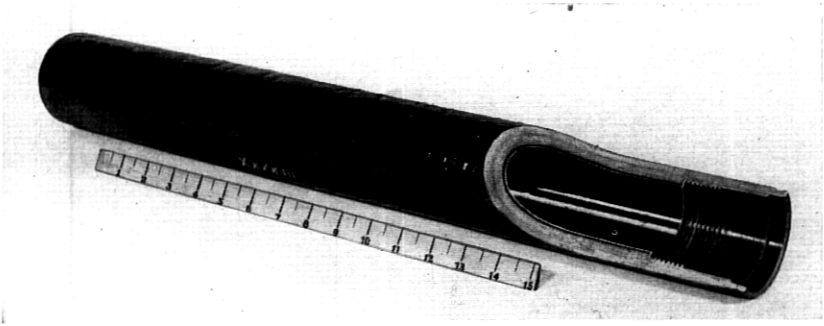

Fig. 2 — 18-inch helix waveguide or mode filter.

is encased in a fiberglass-reinforced plastic jacket. Eighteen-inch lengths of such a structure offer a useful waveguide component for the laboratory and a device for reducing the effects of unwanted modes resulting from imperfections in an otherwise solid-wall waveguide. We are therefore interested in these short lengths for use as mode filters and in longer lengths for assembly into an all-helix waveguide system. The longer units were limited to 112 inches, since this is the present maximum convenient length from a constructional viewpoint. The following paragraphs tell how such units have been constructed.

II. CONSTRUCTION OF HELIX WAVEGUIDE MODE FILTERS

As mentioned previously, the mechanical irregularities in solid-wall waveguide must be minimized. For instance, for operation at 55,000 megacycles it appears desirable and practical to call for an over-all tolerance, including ovality, of ±0.001 inch for a nominal inside pipe diameter of 2.000 inches. At joints, a misalignment producing a step of greater than 0.0005 inch is undesirable. Even with these rigid degrees of tolerance in solid-wall waveguides, the introduction of parasitic modes is such that mode filtering is an additional requisite. The tolerances for the mode filters are just as exacting. Therefore, the casting of these glass-reinforced plastic units must start with a precise mold or mandrel. We have used one made of stainless steel tubing, centerless ground and polished to an outside diameter of 1.998 inches ±0.0005 inch. This nominal diameter for the mandrel allows 0.002 inch curing growth before the inside diameter of the finished product reaches its desired size. Mandrels having a highly polished finish of chrome or stainless steel are preferred, since they resist corrosion by atmospheric elements.

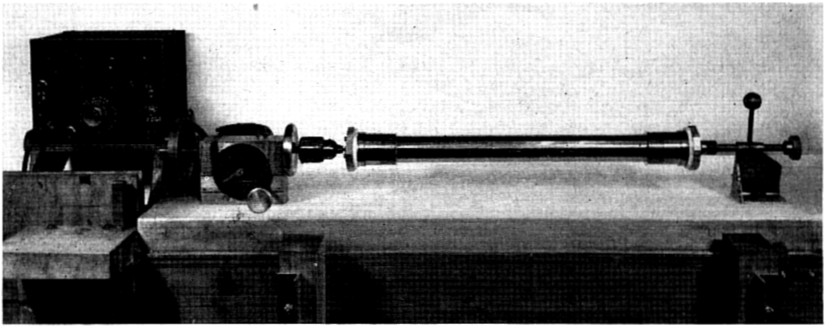

Fig. 3 — Mandrel and machine for winding mode filters.

The mandrel is mounted in a winding machine as shown in Fig. 3. This machine rotates the work while the helix and successive laminated jackets are hand-layered in a manner described subsequently and illustrated in Fig. 4.

After a suitable mold release agent has been applied to the mandrel, the helix is closely wound with plastic-insulated No. 37 copper wire of 0.005 inch over-all diameter. A uniform and appropriate spacing is provided between copper surfaces by the insulation on the wire. Two copper rings terminate the ends of the helix and provide abutment surfaces for joining to solid copper pipe.

After the helix is thoroughly degreased, it is covered with a fiberglass-reinforced plastic jacket consisting of three turns of 0.0015-inch thick woven fiberglass cloth which is impregnated with a thermosetting epoxy resin during lamination. The curing agent used for the epoxy resin is toxic and requires special handling to minimize dermatitis, but its thermosetting characteristics are preferred to the less toxic thermoplastic polyester resins because closer dimensional tolerances can be obtained. The developed wall thickness of this inner jacket is approximately 0.005 inch. The jacket performs two functions. It affords a good mechanical bond to the helix and it provides a transformation of the surface impedance of the lossy jacket presented to the longitudinal currents through the helix.

The lossy jacket is laminated next. It consists of a few turns of tin-oxide coated fiberglass cloth wrapped over the inner jacket and laminated with epoxy resin. This sheath around the helix is the medium in which the energy of unwanted modes is dissipated.

The intermediate jacket surrounding the lossy jacket is laminated with sufficient turns of clear glass cloth to develop a diameter equal to the outer diameter of the copper rings.

The helix waveguide is completed with an outer fiberglass-reinforced plastic jacket which has an over-all diameter of 3 inches. Its purpose is to provide strength. This $\frac{7}{16}$-inch wall jacket consists of additional turns of 0.005-inch clear fiberglass woven cloth which is hand-layered and laminated with epoxy resin extending the entire length of the structure. Before the outer jacket is applied, the areas over the threaded end molds must be filled and laminated with fiberglass roving and tape to the outside diameter of the copper rings, as is indicated in Fig. 4.

The region from the copper ring to the end of the structure forms a coupling. It includes a threaded section followed by a larger-diameter section which facilitates thread alignment when an adjoining section of copper pipe is inserted. This is followed by an end section still larger in diameter. The step formed by the difference in the two latter diameters provides a seat for a rubber "0" ring, which is slipped over the adjoining pipe before its entry and forced against the seat within the chamfered end section. The seal formed by this "0" ring permits evacuation of the assembled line and subsequent filling with dry nitrogen to avoid oxygen and moisture absorption losses.

Throughout the entire construction it is essential to maintain a uniform glass-to-resin content ratio and to apply a uniform tension to the glass cloth. Otherwise, the rigid dimensional requirements cannot be met. A non-uniform layering, commonly experienced with hand-layering, causes a non-uniform wall thickness. This results in non-uniform shrinkage upon curing, which sets up unequal internal stresses that are manifested by ellipticity and a warped axis. Considerable improvement in uniformity of layering has been accomplished by the

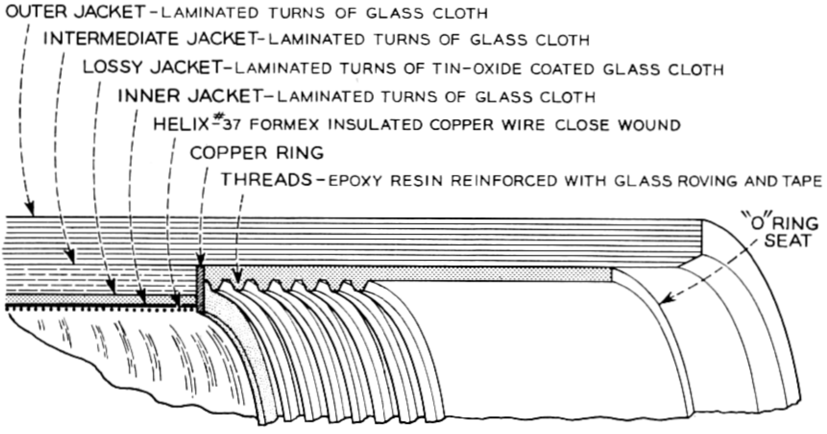

Fig. 4 — Cross-sectional delineation of mode filter.

use of machine-layering, employing glass roving instead of glass cloth. By this means the glass content can be held uniformly at 75 per cent, while the hand-layered products showed 50 to 60 per cent glass content. The higher percentage of glass gives a stronger end product. To preserve a uniform wall thickness it was necessary to rotate the product continuously during layering and subsequent curing.

The curing cycle is also of very great importance in controlling the amount of ellipticity which develops in the finished product. Ellipticity is directly related to the amount of growth in the inside diameter as compared with the diameter of the mandrel on which the helix is wound. During curing, the resin shrinks toward the center of the plastic mass, which means it pulls away from the mandrel. The fiberglass reinforcing material, having a very low heat-expansion coefficient, tends not to move. Therefore, to minimize internal stresses, the shrinkage of the resin must be minimized. This can be done by curing it at as low a temperature as permissible over an extended period of time. During curing at low temperatures there is a sacrifice of heat-resisting qualities and tensile strength for the cured product. But the first of these qualities is of minor concern and the second is compensated for in the structural design.

After the product has been cured and has returned to room temperature, it is ready for the mandrel and thread molds to be extracted. The two ends are unscrewed and the mandrel is withdrawn with an hydraulic ram. The force required to extract the mandrel depends upon the amount of ellipticity in the finished product and the accuracy of the mandrel. The mandrel must meet dimensional requirements which preclude ridges in the surface grinding and present a high degree of polish. With low degrees of ellipticity and a satisfactory mandrel, the extracting force seldom exceeds 300 pounds. A slight amount of cleaning of the product is required after the mandrel is removed.

III. EXTENDED LENGTHS

It has been stated that the transmission characteristics of an all-helix-waveguide system should be superior to a solid-wall waveguide interspersed with 18-inch lengths of mode filters. Such continuous filtering would permit negotiating bends without distorting the signal with reconverted signal energy caused by conversion-reconversion intermode action (Ref. 5, p. 1230). Therefore, research models of helix waveguide have been made in 112-inch lengths. Construction techniques similar to those employed for the 18-inch lengths required using a special

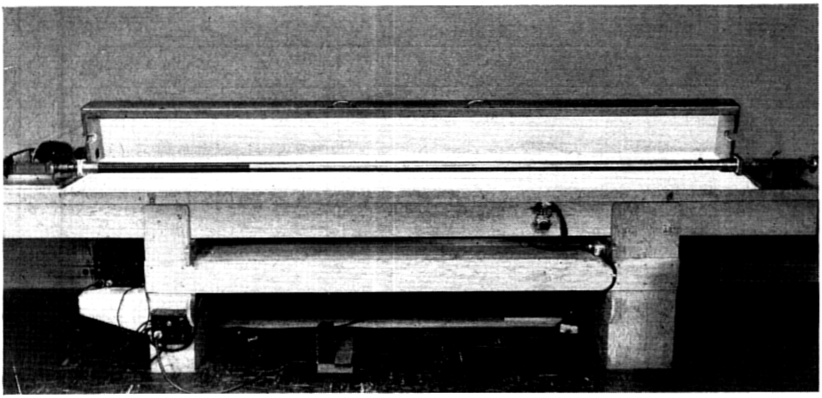

Fig. 5 — Mandrel and oven used in making 112-inch lengths of helix waveguide.

bench with a built-in curing oven which is illustrated in Fig. 5. Because of mechanical difficulties associated with hand-layering, the tolerances achieved on the 112-inch models did not equal those attained on the 18-inch models. With machine construction, it is expected that greater uniformity will be achieved on the longer helices.

IV. OVER-ALL CHARACTERISTICS OF THE HELICES

An inspection of a satisfactorily completed unit reveals the following performance characteristics:

4.1 *Visual*

Sighting through the unit reveals no apparent irregularities in the helical inner wall and, with proper illumination at the far end, one sees light diffraction exhibited as color rings. The outside surface shows a Barcol hardness indicator reading of 50 to 60.

Voids within the wall structure have been readily disclosed by X-rays. This has permitted improved technique. In a well constructed unit, X-rays reveal cross-sectional wall areas with void-free laminations. This type of examination verifies the fact that the number of voids is negligible in jackets constructed with machine-wound glass roving rather than with hand-layered glass cloth.

4.2 *Dimensional*

By means of an air gauge, maximum and minimum diameters are recorded at every inch of axial length, since it is the difference between

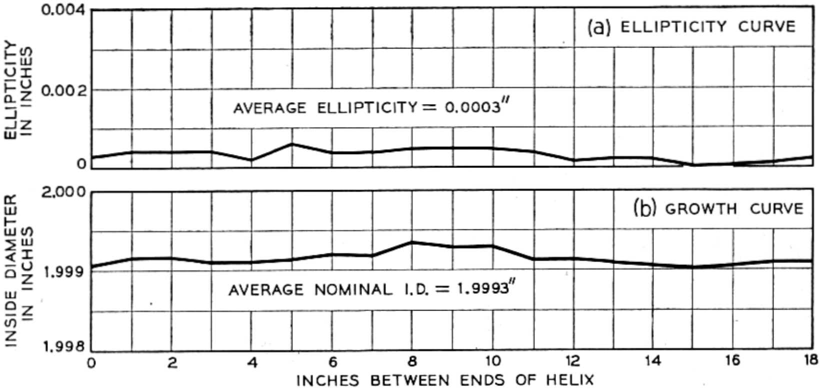

Fig. 6 — (a) Curve showing ellipticity in an 18-inch mode filter, (b) curve showing nominal inside diameters of an 18-inch mode filter.

the maximum and minimum diameters at any point along the axis that expresses the degree of ellipticity. A typical plot of this information is shown in Fig. 6(a). In Fig. 6(b) the average diameter computed from the above data is plotted as a function of position along the axis. The goal is a minimum degree of ellipticity and an average nominal inside diameter of 2.000 inches. For the 18-inch units, we are currently accepting degrees of ellipticity as herein defined which do not exceed 0.002 inch, with an average over-all ellipticity not greater than 0.001 inch. For the 112-inch units, the current degrees of ellipticity do not exceed 0.006 inch and the over-all average ellipticity is 0.0027 inch.

4.3 *Bending Stiffness*

When the mode filters are inserted at intervals in an otherwise solid-wall copper pipe line it is desirable to have their bending stiffness comparable, if not equal to, that of the copper pipe. Such structural uniformity throughout the line is necessary to insure that serpentine deformation caused by thermal expansion will be uniform in the entire line. If this were not so, a concentrated bend would occur at the weakest point, which would result in excessive axial tilt and introduce undesirable mode conversion. Therefore, the design of the mode filter is such that its resistance to bending, which is proportional to the product of its structural moment of inertia and its modulus of elasticity, must approximate that of the copper pipe. A jacket wall $\frac{5}{8}$ inch thick provides a sufficiently large structural moment of inertia to offset the greater modulus of elasticity for the copper, which is 18 × 10^6 lbs. per sq. in. The modulus of elasticity of the reinforced plastic structure measures 2.5 × 10^6 lbs. per sq. in.

4.4 *Electrical*

The circular-electric-wave attenuation coefficient of the helices may be measured with appropriate apparatus which treats the unit as a resonant cavity. Such tests at 55 kmc* indicate that at present the best attenuation coefficient is 1.9 times that calculated for perfect solid-wall copper waveguide of the same diameter.

The other electrical performance characteristics of these helices will will be covered in another paper; the general problem of maximizing the loss for undesired modes of propagation is covered in detail by S. P. Morgan and J. A. Young.[7]

V. CONCLUSIONS

Sections of helix waveguide in 18- and 112-inch lengths have been made at the Holmdel Laboratory of Bell Telephone Laboratories. The shorter lengths of helix waveguide serve as mode filters to correct for conversion-reconversion effects in a transmission line composed mainly of solid-wall cylindrical waveguide. The longer helix units will provide continuous filtering when used exclusively in a helix-waveguide system. This becomes increasingly attractive for wide-band microwave transmission in the spectrum from 35,000 to 75,000 megacycles per second.

ACKNOWLEDGMENT

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* The 55-kmc attenuation measurements were made by J. A. Young of the Laboratories.

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